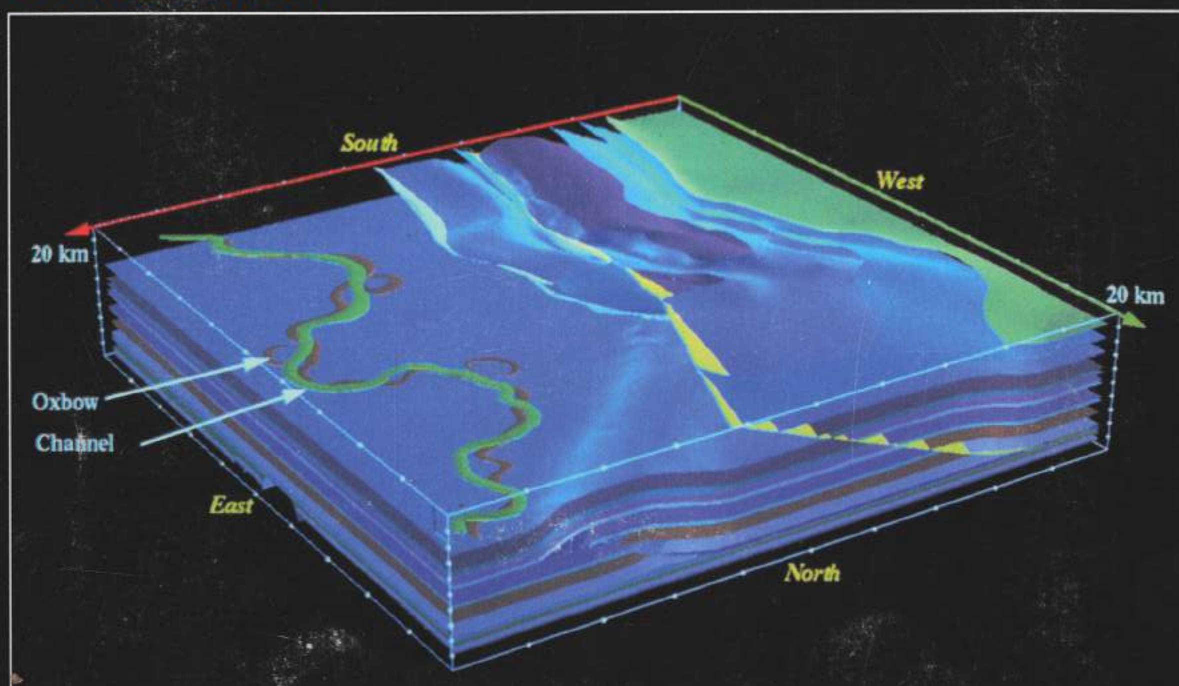
Overthrust Model



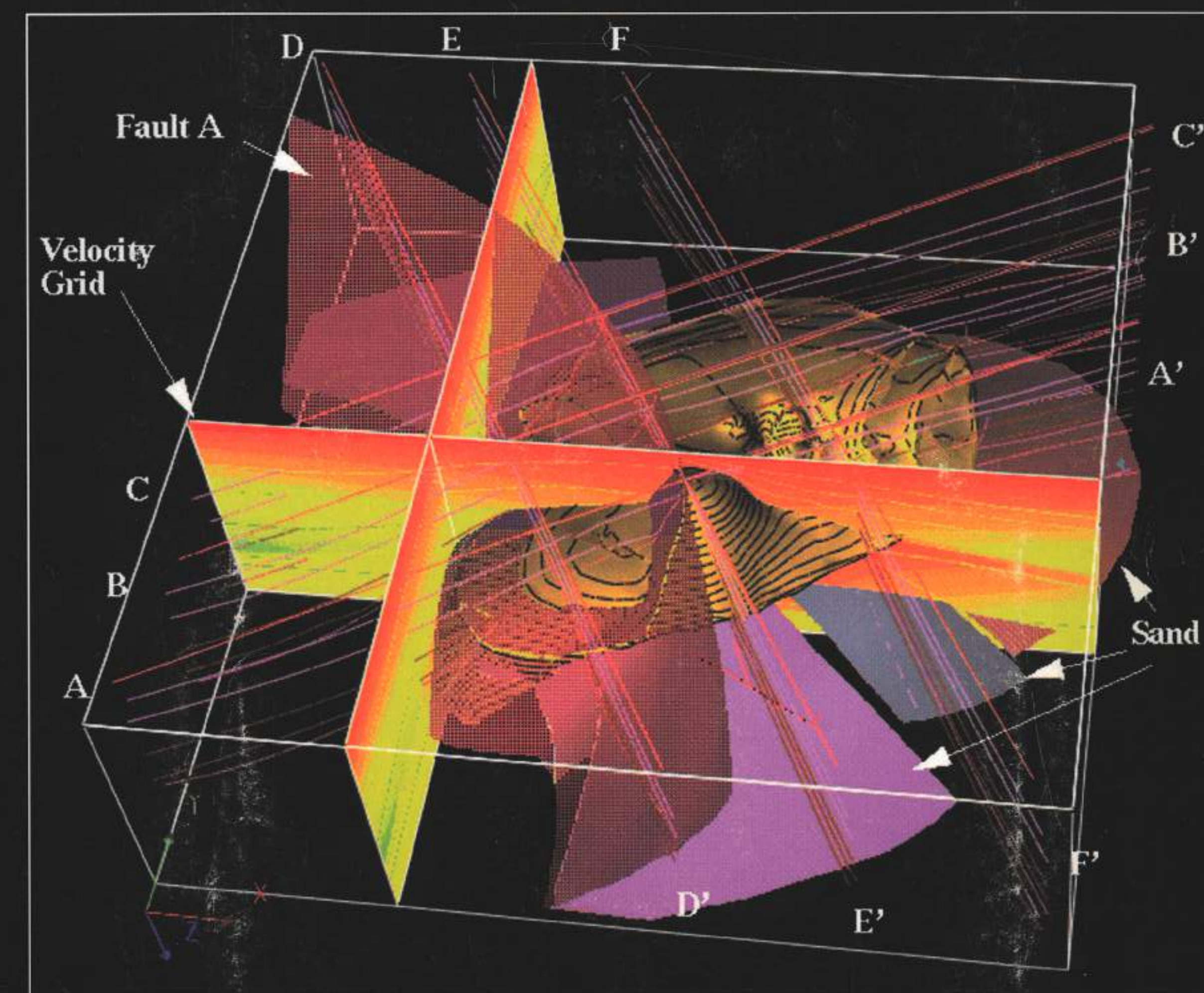
SEG EAGE

A joint project of the Society of Exploration Geophysicists
and the European Association of Geoscientists and Engineers

SEG/EAGE 3-D Modeling Series No. 1

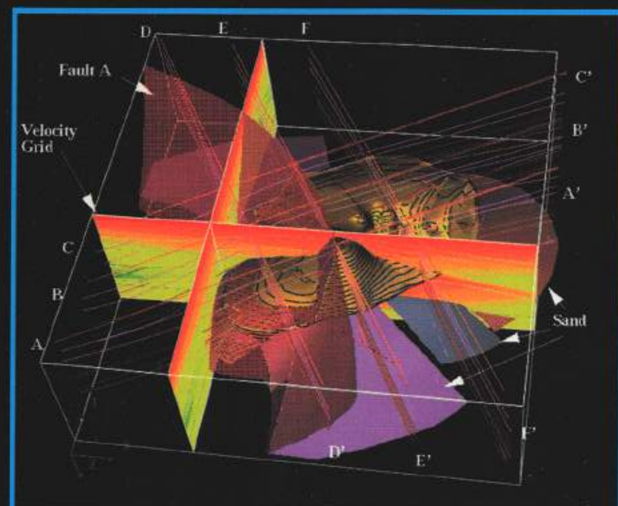
3-D Salt and Overthrust Models

Salt Model



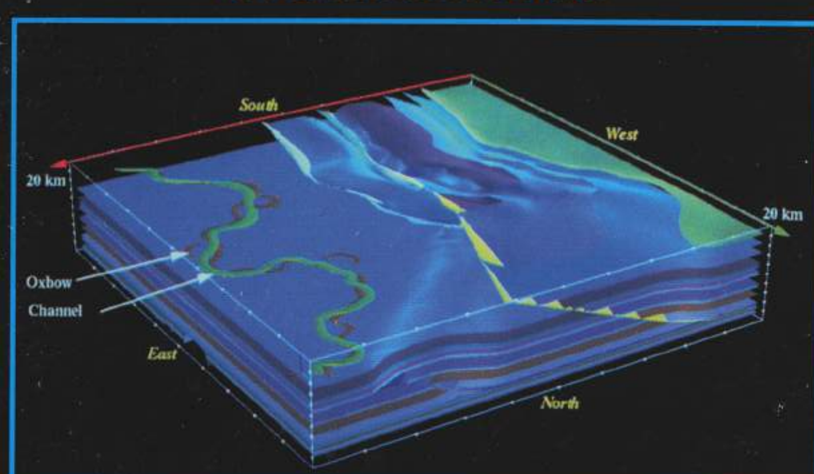
By Fred Aminzadeh, Jean Brac, and Tim Kunz

Salt Model



Tim Kunz

Overthrust Model



Jean Brac

See *Read Me* files for disk use instructions

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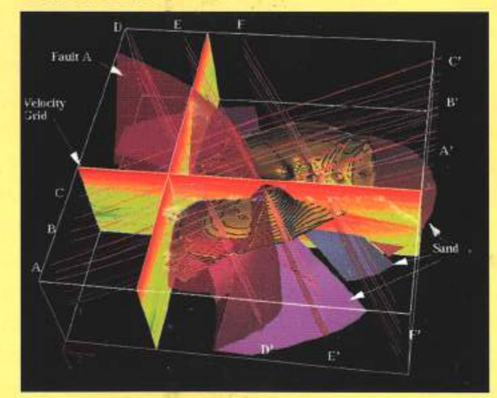
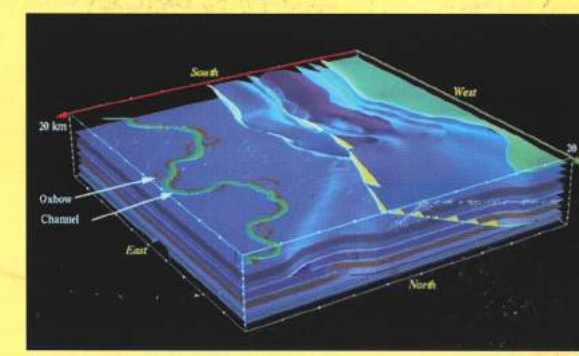


Overthrust Model



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SEG/EAGE 3-D Salt and Overthrust Models*

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ABSTRACT

As a result of collaborative efforts of geophysicists, geologists and computer scientists from more than fifty different organizations, two 3-D geologic models have been designed, and associated 3-D synthetic seismic data have been generated. This work was sponsored by the Society of Exploration Geophysicists (SEG), European Association of Geoscientists and Engineers (EAGE), and for the most part, funded by the United States Department of Energy National Laboratories with contributions from the petroleum industry and various research organizations. The project is usually referred to as the SEG/EAGE Modeling or SEM project. The two salt and overthrust 3-D models and the respective synthetic data sets will be made available to both the oil industry and academia. This SEM project has been a sizeable undertaking with computational requirements of several million dollars resulting in three terabytes of data. All three phases of the project have been completed. "Classic Data Sets" containing subsets of calculations conducted for Phases A, B, and C have been defined. Any other subsets of data from the whole data set, currently residing at Lawrence Livermore National Laboratory (LLNL), could be extracted using a procedure devised by LLNL. Plans are under way to identify a permanent site. These data sets have already been used by many for testing, validating processing algorithms, and aiding for survey design. Their usage as standard 3-D data sets is expected to increase for many years.

INTRODUCTION

Three-dimensional model data are useful for testing 3-D processing algorithms (e.g., migration, velocity analysis, multiple suppression, etc.), understanding wave propagation in a complex 3-D medium, choosing proper acquisition parameters, and testing various data compression and data transmission techniques. They can also be used for training as well as benchmarking different hardware platforms.

Examples of models that have gained widespread popularity for various types of testing and benchmarking are the 3-D French model (French, 1974) and the 2-D Marmousi model (Lailly and Versteeg, 1990). In recent years, advances in computer technology have enabled bigger problems to be modeled. This capability, combined with the ever increasing complexity of structures that are being explored and developed, has necessitated construction of more complicated 3-D models.

After a number of surveys of the SEG and EAGE memberships and discussions during workshops, we have made final decisions on different aspects of the 3-D models. Some issues that had to be decided were:

- structural/stratigraphic nature of the model
- model representation
- acquisition parameters
- numerical techniques for generation of seismograms
- model type (acoustic vs elastic)
- computer resources requirements and contributors.

Given the constraints of available computer resources and the immediate needs of the industry, the following compromises had to be made:

1) structural problems are the main focus of this modeling effort, although the overthrust model includes some stratigraphic features (channel sand),
2) geological models are represented using University of Nancy, GOCAD software,
3) acquisition parameters are decided in different phases of the project based on the available resources,
4) marine acquisition geometry is used for both models to avoid land topography problems,
5) the finite difference method is used for calculations,
6) the calculations are based on an acoustic medium, and
7) computer resources of the U. S. National Laboratories are used to construct the model responses.

Two acoustic models were chosen to carry out the simulation: a salt dome model with features similar to those of the U. S. Gulf of Mexico and an overthrust model mimicking real overthrusts of South America. Working groups were formed to finalize respective details of the project, such as, (a) construction of the overthrust model, (b) construction of the salt dome model, and (c) selection and porting the finite differences codes to different platforms and execution of the numerical computations.

Other working groups have been formed to help finalize the survey parameters and to develop a

* Adapted from Chapter 28 of *Applications of 3-D Seismic Data to Exploration and Production*, SEG Geophysical Developments Series No. 5, AAPG Studies in Geology No. 42, P. Weimer and T. Davis, Eds. 1996.

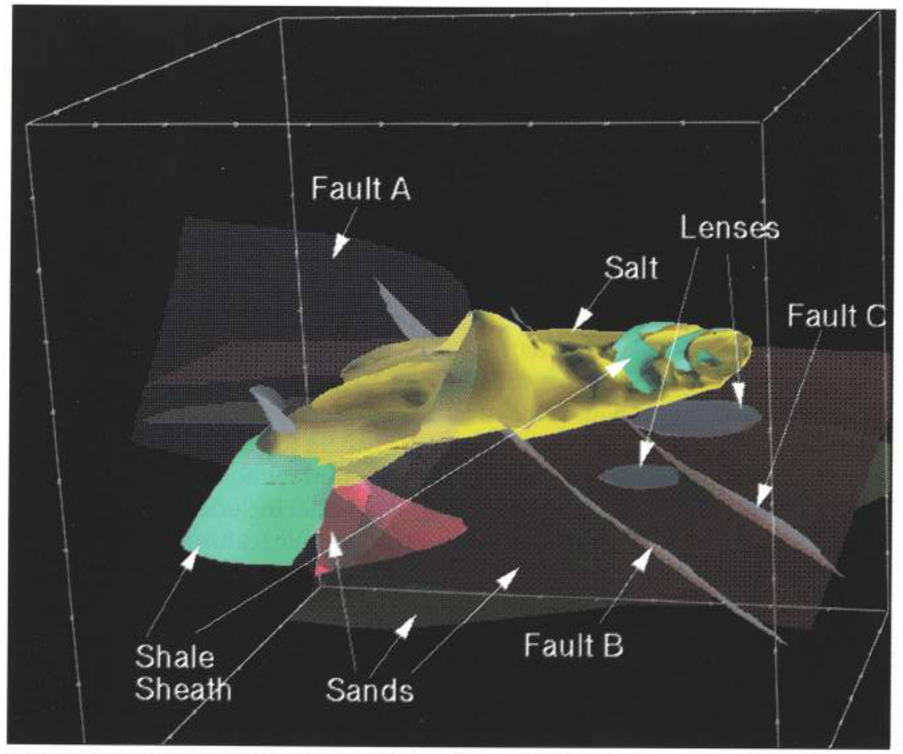


Figure 1. The 3-D perspective of the salt model (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists; permission for use on CD-ROM courtesy of Datapages, Inc.).

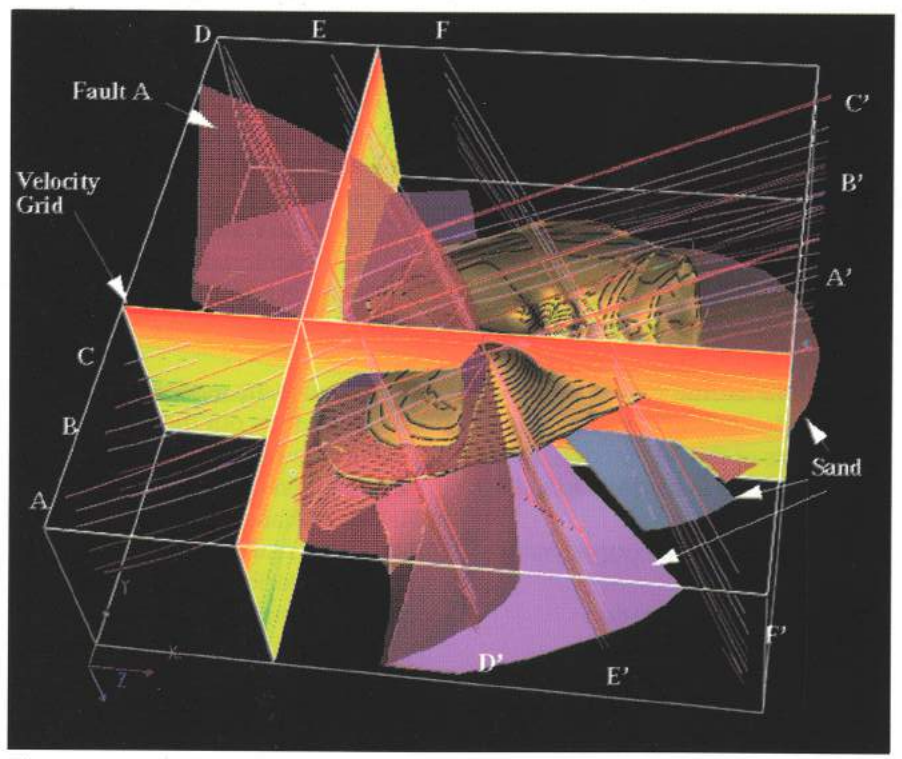


Figure 2. The salt model with two velocity profiles (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists; permission for use on CD-ROM courtesy of Datapages, Inc.).

scheme for storing and distributing large volumes of the numerical calculations. For other background information and more details about the evolution of this project, refer to Aminzadeh et al. (1994a, 1994b, 1995, 1996) and Kunz et al. (1995).

SALT MODEL

The design of the salt model was accomplished through the participation of twenty-seven representatives (experienced in salt tectonics, seismic modeling, and seismic imaging) from twenty-three organizations representing oil companies, seismic contractors, and academia. It was agreed by these representatives to base the salt model on a typical Gulf Coast salt structure. Special care was taken to ensure both its geological reasonability and its adequacy as a testing mechanism for seismic imaging algorithms (particularly subsalt).

Figure 1 shows the 3-D perspective of the salt model with the salt sill, different faults, sand bodies and lenses. The salt model exhibits the following major features: (1) a northwestwardly plunging stock; (2) a secondary reactivation crest, located southward of the stock; (3) a broad, low relief eastern flank; (4) a faulted southern flank with minor toe thrust; and, (5) a rounded overhang on the west flank. The northern flank is bounded by a counter-regional fault, with attendant downthrown roll-over structure in the outboard section. Two down-to-the-basin faults occur beneath the salt sill; one of which offsets the salt base. The salt edge cross cuts stratigraphy at a low angle and varies in shape around the sill perimeter. The eastern flank exhibits a mildly downturned edge. The southern flank exhibits an upturned edge; the western flank has a rounded edge; and the northeastern edge of the salt contains a salt weld. The overall model dimensions are 13.5 x 13.5 x 4.2 km in the x, y, z directions, respectively. The maximum sill length is approximately 9.5 km; and the maximum

sill width is approximately 6.6 km. The salt crest is at approximately 325 m.

The model contains five sands. The two shallowest sands truncate against the sill base. One of the intermediate sands is stratigraphically isolated, and the other conforms to the subsalt anticline. The model contains a shale sheath that is modeled to be geopressured. The seafloor (bathymetry) map exhibits a counterregional fault scarp and a bathymetric rise associated with the sill crest. The map also exhibits a shelf break at the southeast end of the model.

This model is designed in part to be able to test various imaging algorithms in different geologic settings: salt flank, salt overhang and subsalt. The velocity model is generated using a 20-meter grid with 15 Hz center frequency for the wavelet. The velocities surrounding the salt body are typical of Gulf of Mexico sediments and are described by compaction gradients based on K-V_0 curves (V_0 is the initial velocity, and K is the velocity gradient that varies spatially) and a geopressure surface. The following expression is used to define the 3-D velocity field:

$$V(x,y,z) = V_0 + z\,K(x,y) - GP \quad (1)$$

where GP is the deceleration term for velocities below the geopressure surface. Water and salt velocities and GP are chosen to be 1500, 4481, and 46 respectively. Figure 2 shows another 3-D display of the model with two perpendicular 2-D velocity profiles. Color velocity scales to the left of Figure 3 are in meters per second, with blue indicating the high salt velocities. Green color indicates relatively lower sediment velocities of the overpressure zones.

We make a constant density assumption due to the limitations of the finited difference code. The model also contains a flat horizon above the model basement which may be used as a means to evaluate the quality of seismic imaging algorithms. Since the constant density assumption and the simple velocity gradient structure given by Equation 1 result in no reflectivity in the sediment surrounding the salt, we use a "spike" method to create reflections from geologic boundaries. This method increases the velocity of the function for each successive layer as shown in Figure 4. As shown in Figure 5, the synthetic seismogram of the AA' cross section of Figure 3 exhibits proper reflections from geologic boundaries using the spike velocity profile of Figure 4.

Appendix A gives the table of contents of the CD-ROM containing the salt model, the respective velocity models, and the sample synthetic classic data sets.

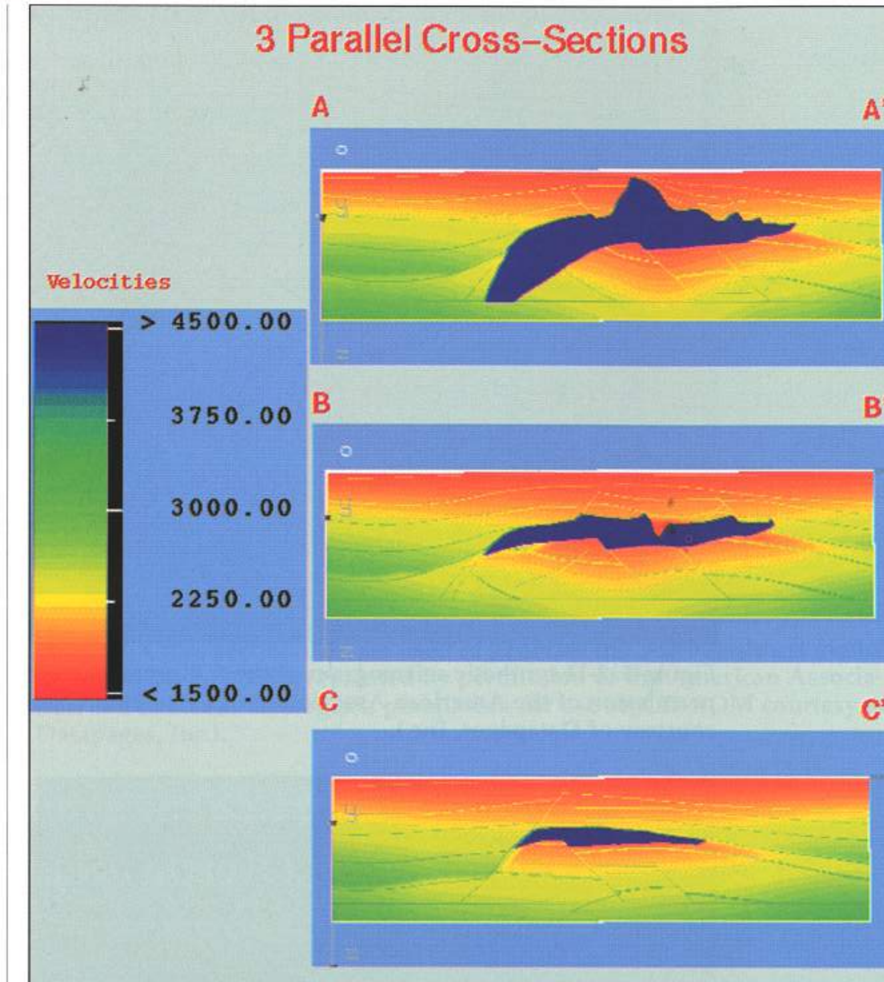
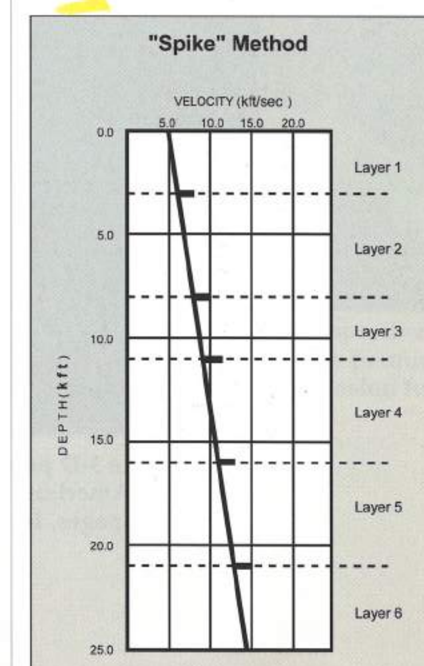


Figure 3. Velocity profiles on three parallel cross sections and Figure 4. (below) Velocity profile using the "spike" method (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists; permission for use on CD-ROM courtesy of Datapages, Inc.).



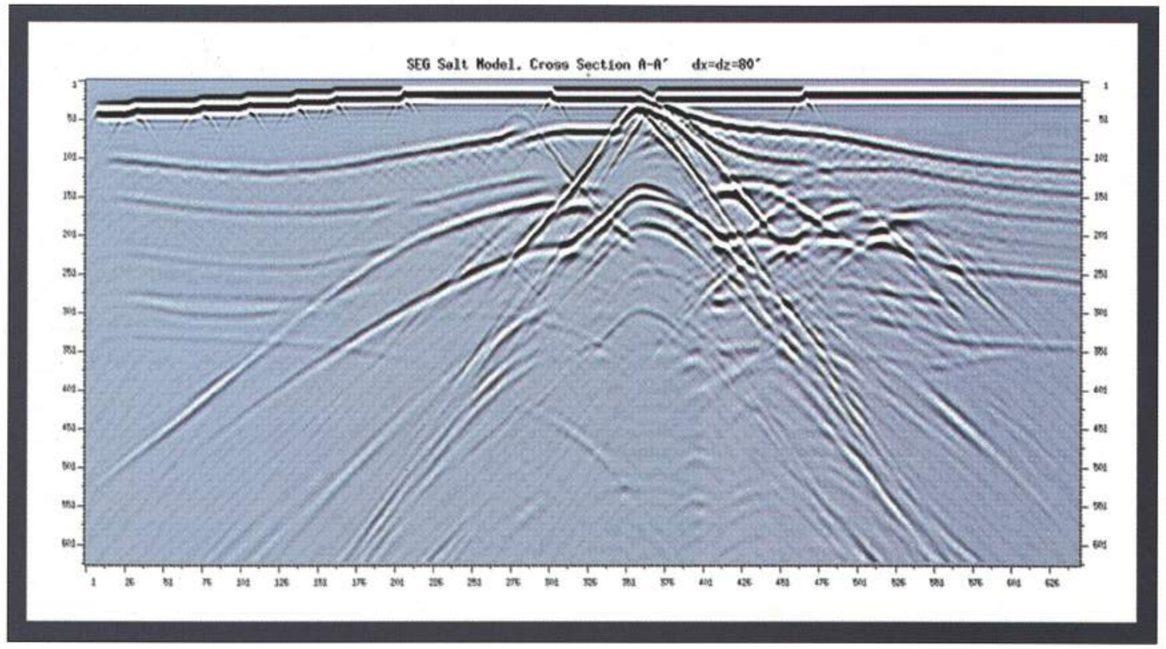


Figure 5. 2-D synthetic seismogram of the AA' cross section (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists; permission for use on CD-ROM courtesy of Datapages, Inc.).

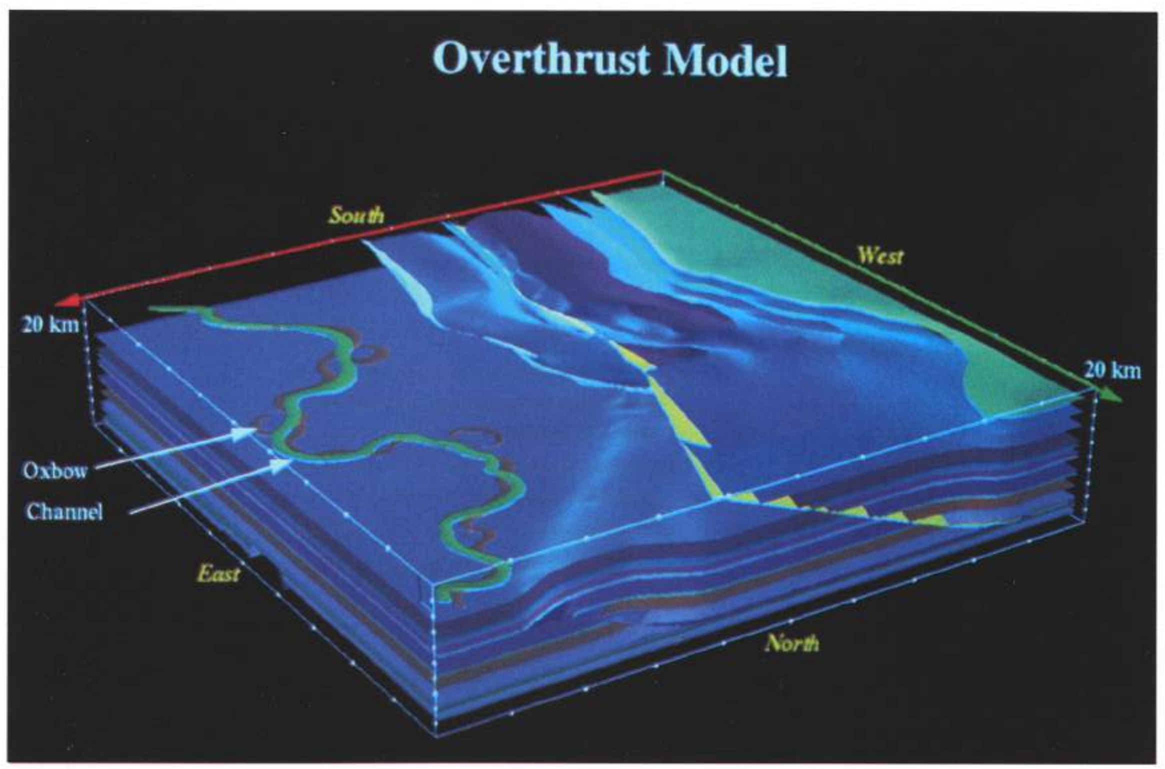


Figure 6. The 3-D perspective of the overthrust model (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists; permission for use on CD-ROM courtesy of Datapages, Inc.).

OVERTHRUST MODEL

A complex thrusted sedimentary succession has been constructed on top of a structurally decoupled extensional and rift basement block. The thrust unit has been built from 2-D balanced cross section. Figure 6 shows 3-D perspective of the overthrust model. The basement (not shown) underneath the overthrust structure includes an extensional fault block system, with a sediment cover on the basement blocks. Above this, there is an erosional truncation, and there is a structural uncoupling between basal and uppermost units. A petroleum trap has been introduced between the two reverse faults, in the heavily folded thrust. Also observe the sand channel included in the west side of the model. Figure 7 shows the original 2-D cross sections that were used in constructing the 3-D overthrust model. The model represents two converging thrusts plus an additional blind thrust which dies out laterally.

The basement has been validated by the Fault Analysis Group of the University of Liverpool. The model is overlain by a flat sedimentary layer underneath the sea bed. Figure 8 shows various cross sections of the overthrust model. The model has dimensions of 20 x 20 x 3.5 km giving a zone of maximum seismic coverage of 10 x 10 x 3.5 km. In total, it has seventeen layers. The model presents a varying degree of complexity, with a central thrust faulted anticline, and an external monocline and flat zone. The top of the overthrust is eroded and covered by a surface layer to represent recent sediments. Channels and crevasse splay lenses are present in some layers. The layer thickness is preserved and the percentage shortening at any point across the thrust structure is approximately constant. Fault planes have been checked by 3-D visualization to ensure smoothness and regularity. Figure 9 shows the process by which fault rifts were built. The basement is comprised of

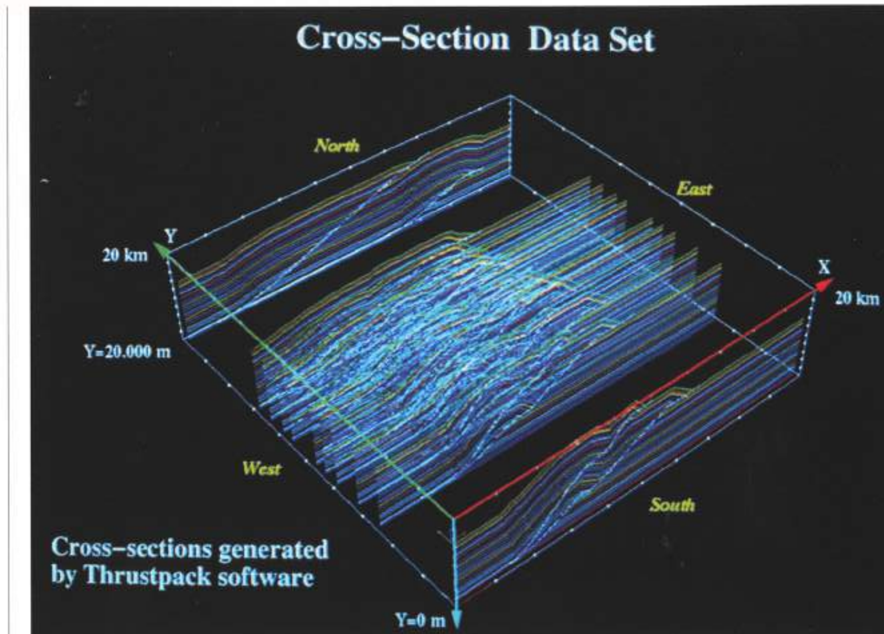


Figure 7. Cross section data set used to generate the 3-D overthrust model (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists; permission for use on CD-ROM courtesy of Datapages, Inc.).

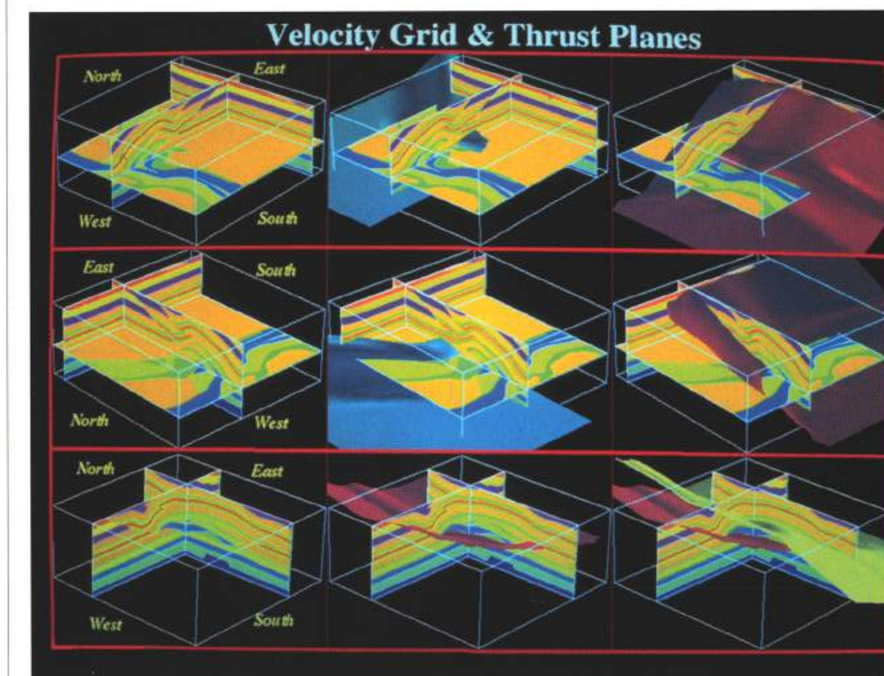


Figure 8. 2-D slices through the overthrust model showing the respective positions of the thrust planes (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists; permission for use on CD-ROM courtesy of Datapages, Inc.).

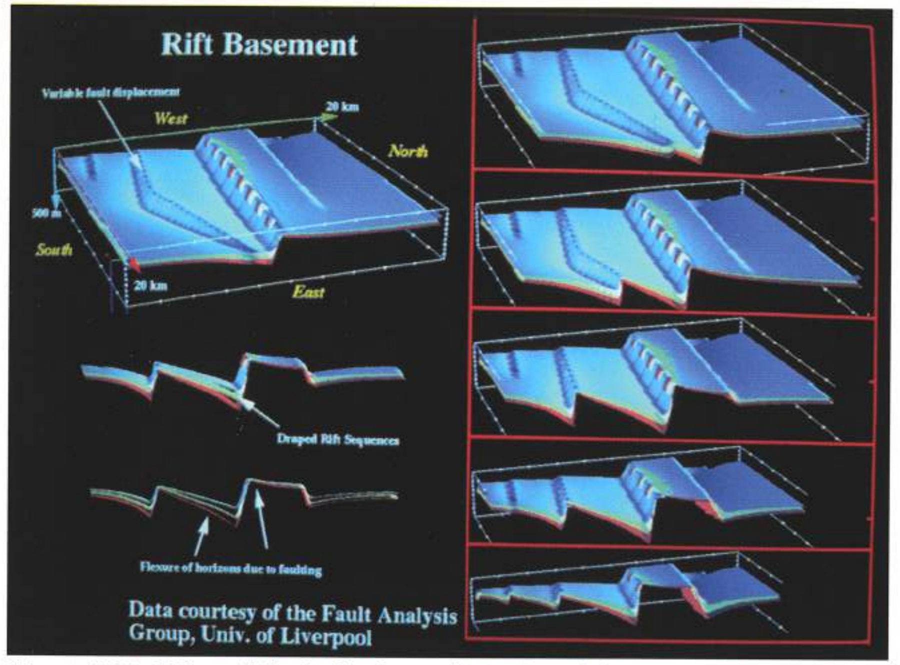


Figure 9. Building of the fault planes (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists, courtesy of the fault seal analysis group, University of Liverpool; permission for use on CD-ROM courtesy of Datapages, Inc.).

alternating layers of carbonate and siliciclastic sedimentary rocks which drape tilted, extensional fault blocks.

There are petroleum traps in the tilted strata draping the middle block. The upper boundary of this extensional unit is an erosional truncation. This layer is in turn overlain by a sedimentary succession in which an initial salt layer is overlain by a predominantly marine sedimentary stratigraphy comprised of two major carbonate successions and siliciclastic and argillaceous sediments. The salt layer acts as decollement surface for two thrust planes which deform the upper sediment column. The lower of the two thrusts converges laterally with the upper plane. The layers in the area bounded by the faults are folded into an anticline with a fold axis that varies laterally to create a closed petroleum trap in the sandstone layer. The folds contain reverse limbs at the point of minimum structural depth of the structure. There is a bulge in the footwall of the thrust sequences that dies out laterally. The thrust layers are capped by a thin sedimentary veneer and a sea layer.

Several constructive criticisms on the model have been provided by various companies, with the major recommendations being:

- The model should be an onshore structure, rather than an offshore one, with substantial topography and a complex weathering zone.
- The model should include even more 3-D properties.
- The velocity distribution should be constructed from an existing data base.
- Some features (imbrication of thin beds, lenses, pinchouts, etc.) should be included to address the problem of seismic resolution.

These features, except the topography, have been included in the final model. The choices made were mostly constrained by the available computational resources and the limitations of the code chosen based on various other considerations.

The majority of the work in connection with the construction of the overthrust model was carried out in the Institut Français du Pétrole with participation from many organizations as well as oil companies, seismic contractors and academia, including the fault analysis group of University of Liverpool and GOCAD group at the University of Nancy. Appendix B gives the table of contents of the CD-ROMs containing the overthrust model, the respective velocity models, and the sample synthetic classic data sets.

COMPUTATIONS AND THE 3-D FINITE DIFFERENCE CODE

We concluded early on that 3-D structural problems should be the primary focus of this effort. Because extensive wave propagation computations through an elastic medium in a survey size setting are still beyond reach of today's technologies, a full-sized seismic survey will therefore be limited to acoustic computations only.

Several 3-D finite difference (FD) codes have been provided by various organizations for acoustic wave propagation computations in the 3-D model. The Computation Working Group conducted extensive evaluations of these candidate codes. The finite difference 3-D wave propagation code provided by the Institut Français du Pétrole, with a second-order scheme in time and a 10th-order scheme in space, was chosen for the entire simulation. The time steps were 1.14 milliseconds, while the space steps (x, y, z) were 25 m. The parallel version of this code is implemented on different super computers: Paragon, Meiko CS-2, Cray Research c-916, Connection Machine CM-5, Fujitsu VP 2400 and Fujitsu VPP500. The entire calculation is divided into segments to be carried out on various machines located in different laboratories. For this reason, extensive work was done to ensure that different platforms yield the same results.

These calculations are done under the DOE (Department of Energy) Gas and Oil National Information Infrastructure (GONII) project and with a contribution of the IFP resources. Four national laboratories: Lawrence Livermore, Los Alamos, Oak Ridge, and Sandia — are contributing to these efforts. Aside from computation, resources and technologies available at the national laboratories, such as networking, high speed I/O, mass data storage, collaborative tools, distributed computing, visualization, and computer security are being used to increase the utility of this project to the oil industry.

SALT CALCULATION

The **Phase A** acquisition program for the salt model contains two perpendicular lines, which span the model with a shot spacing of 80 m. Each of these lines is a broad-line swath across the model. Figure 10 shows the orientation of these lines and the receiver grid pattern for shot line 1. Each line has 138 shots. In addition, two down-hole shots were calculated at depth locations of 900 and 2300 m at a vertical well located at the intersection of the two lines. All Phase A calculations (total of 278 shots) have been completed. The data have been stored on the online storage system at LLNL.

The **Phase B** acquisition program for the salt model contains 35 shot lines which span the model with a shot spacing of 320 m. All of the lines are broad-line swaths across the model. In Figure 11, the large square with the coarse grid displays the acquisition geometry. In total, Phase B represents a coarse source spacing 3-D survey across the entire model. The two wells in the salt model are included whenever the wells are within the computational grid. All Phase B calculations have been completed and the data now reside on the online storage system at LLNL.

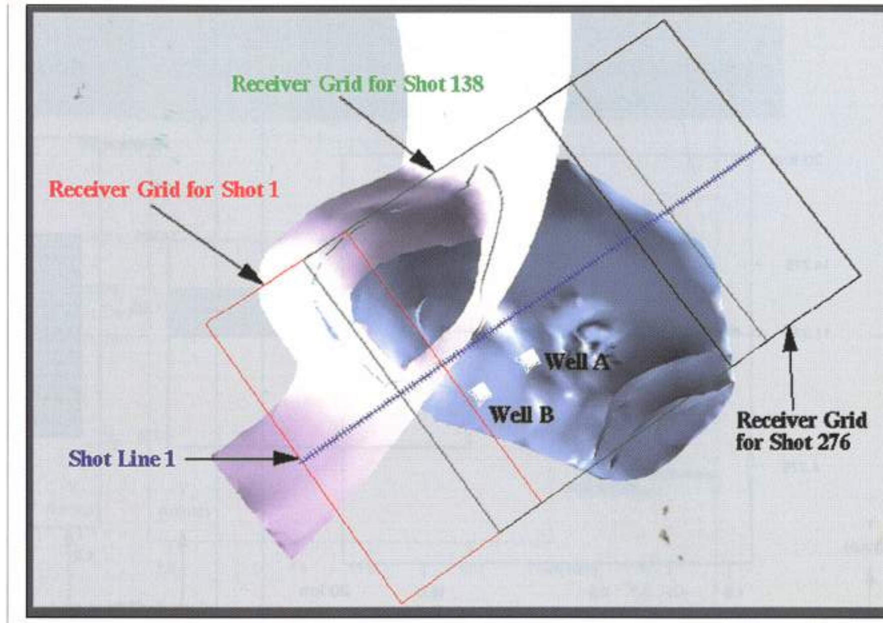


Figure 10. Orientation of two lines for Phase A calculations (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists; permission for use on CD-ROM courtesy of Datapages, Inc.).

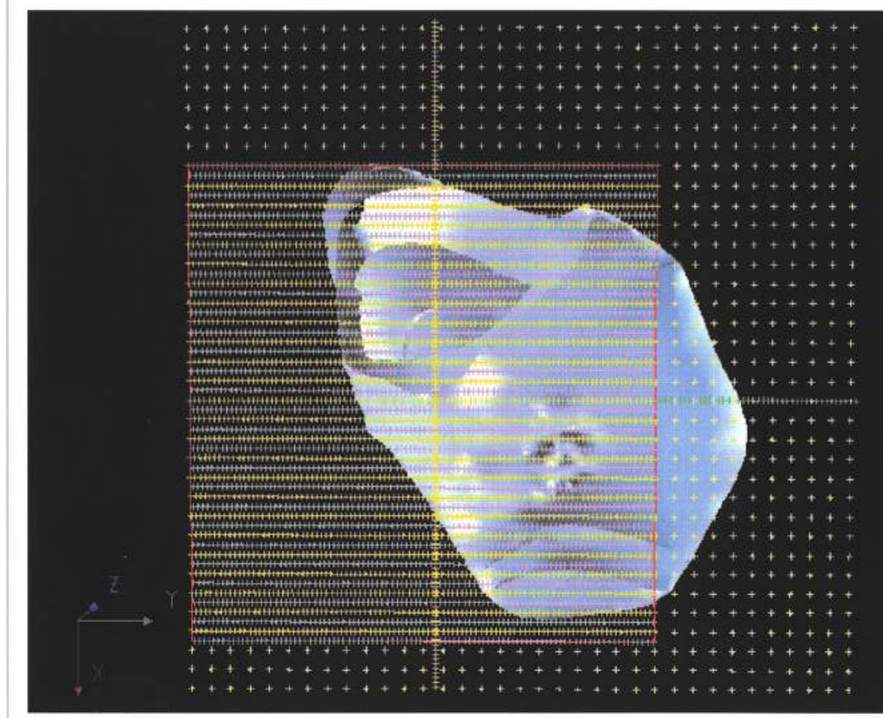


Figure 11. Phase B and Phase C acquisition with an overlay of Phase A lines (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists; permission for use on CD-ROM courtesy of Datapages, Inc.).

Phase C increases the number of total shots by a factor of four. The acquisition for Phase C consists of in-filling Phase B shots within a selected area of the model so the resulting shots have an 80-meter shot spacing inline and a 160-meter shot spacing cross line (Figure 11). The selected area contains 24 shot lines, each containing 25 shots from Phase B. To infill these shots to an 80-meter spacing inline required an additional 1728 shots. To reduce the cross line shot spacing to 160 m required an additional 25 shot lines. Each of these new shot lines are offset 40 m in the inline direction from the Phase B lines to simulate a typical marine acquisition. Phase C used 97 shots from Phase A, 600 shots from Phase B, and an addi-

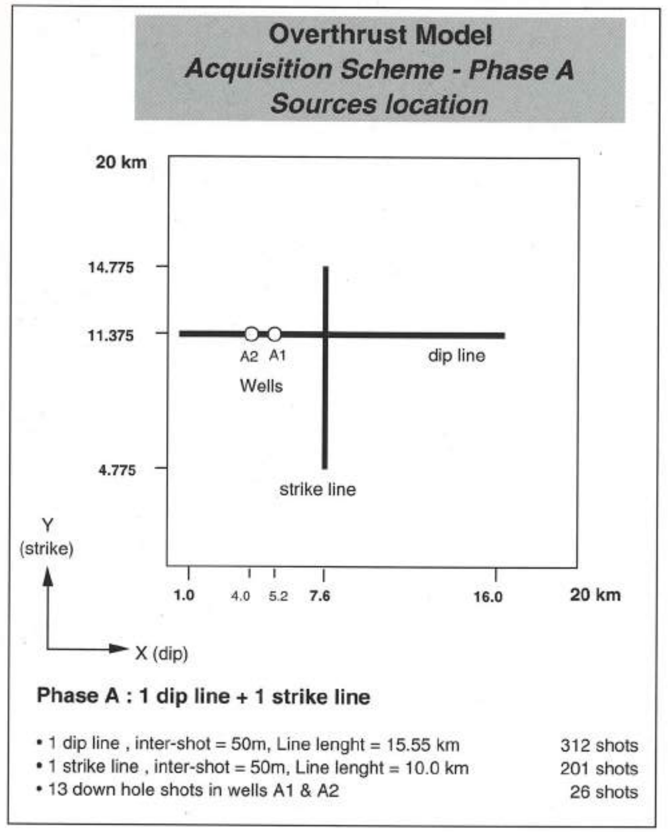


Figure 12a. Overthrust acquisition for Phase A.

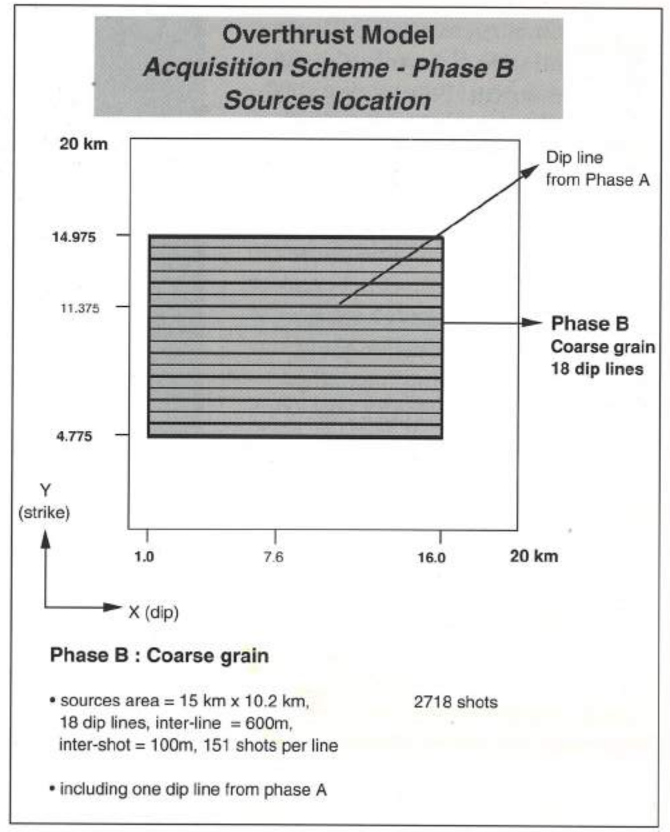


Figure 12b. Overthrust acquisition for Phase B.

tional 4103 new shots. Figure 11 shows the two crossing shot lines from Phase A, in yellow and green, and the coarse shots from Phase B. The Phase C infill shot lines are displayed in yellow, and the new shot lines for Phase C are shown in purple. To be consistent with shots previously acquired, the new shots for Phase C will be acquired using the 279 x 279 receiver geometry used in Phases A and B. As can be seen in Figure 11, Phase C provides dense 3-D shot coverage over the stem, crest, and toe rollers of the salt.

OVERTHRUST CALCULATION

The acquisition plan was organized in three phases—A, B, and C—corresponding to the following types of acquisition: two perpendicular lines of shots, a large coarse grain shot survey, and a small thin grain survey. Real production began in February 1995 and was completed in May 1996.

Phase A

Phase A (Figure 12a) consists of two perpendicular lines:

- *a dip line* of 312 shots points. The shots interval is 50 m.
- *a strike line* of 210 shots points, perpendicular to the first one, with an inter-shot spacing equal to 50 m. It is located above the main thrust.

The Phase A includes also complementary well acquisitions:

- *Normal incidence VSPs*: a set of fifty-two wells is located along the dip line in order to record normal incidence VSPs. The objective of this acquisition is to help the interpretation of the surface seismic events.
- *Two-dimensional walk-away*: a large 2-D walk-away is recorded during the computation of the dip line shots. One hundred sixty-one receivers are distributed in a well located on the dip line at X=5200 m, as well as in four adjacent columns (in order to access to the three components of the pressure gradient). This well and its four neighbors record 126 surface shots (along the dip line) for offsets smaller than 3.1 km.
- *Reverse 3-D walk-away*: to complete this borehole acquisition, a reverse 3-D walk-away is computed in the well mentioned above, constituted of 13 down-hole shots. All surface receivers with offsets smaller than 3000 m are recorded.

Phase B

Phase B (Figure 12b) corresponds to a "Coarse Source Spacing" 3-D acquisition, on an area of 15 km x 10.2 km, aimed to constitute a land type survey. It covers most of the structures of the model, in particular the anticline thrust limited by the two main faults. From the computational point of view, this phase is made of 17 dip lines of shots with 600 m between lines and 100 m between shots in the dip direction. Including in Phase B the dip line already computed in Phase A, the Phase B from the acquisition point of view is therefore constituted of 18 dip lines.

Phase C

Phase C (Figure 12c) consists in the acquisition of a dense repartition of shots (100 m between shots in X and Y directions) in a rectangle of 10 km in the dip direction (101 shots) and 2.4 km in the strike direction (25 lines). It is aimed to constitute marine type surveys. This area covers the intersection of the two main faults of the overthrust model.

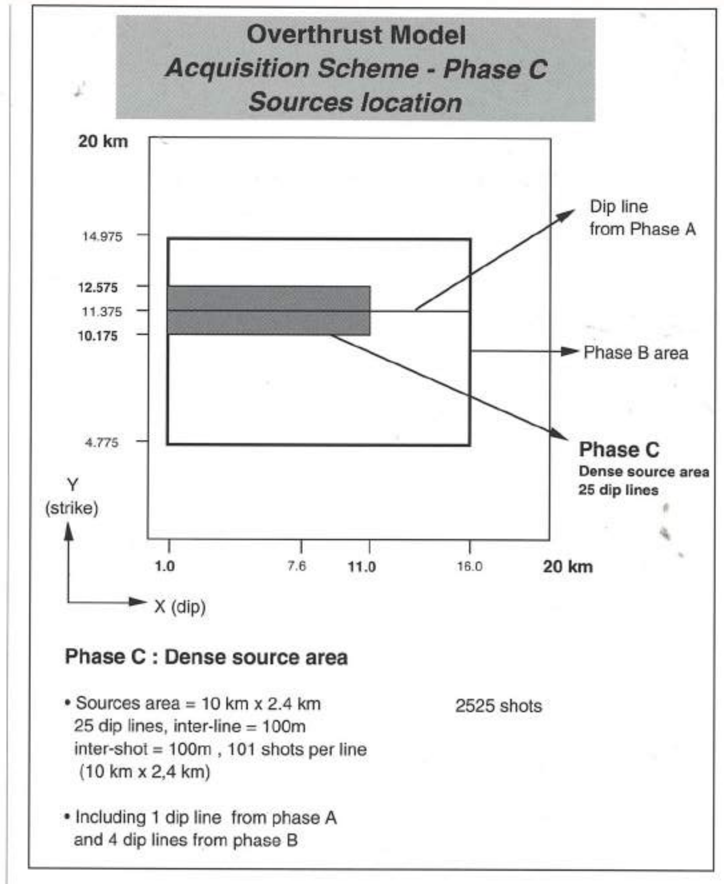


Figure 12c. Overthrust acquisition for Phase C.

LLNL's FAST STORAGE FACILITY FOR SEM DATA SET

Lawrence Livermore National Laboratory (LLNL) is developing tools for accessing the nearly one terabyte of modeling data. This SEM data set (SEMD) resides at LLNL's FAST storage facility. Because of the massive size of the modeling project data, tools for easily extracting useful subsets of data are crucial. Four distinct methods for doing these extractions are being pursued: classic data sets, Web-based forms, an X-Windows based tool, and an SEG-P1 parser.

The first three methods can be accessed via the World Wide Web (WWW). The easiest option for the user is to directly download from a set of pre-defined "classic" data sets extracted from the SEMD. These classic data sets, which are interesting subsets of data culled from the project data, are defined next.

For users wanting to build their own subsets of the SEMD, WWW forms for selecting the model, lines, and seismic traces of interest will be provided. Once the selection has been made, the requested data will automatically be extracted from the FAST storage system and will be sent to the requester in the desired format on the Internet. Interactive searching and browsing of the project data will also be provided via WWW forms.

A more sophisticated X-based graphical interface to SEMD extraction will also be provided. This tool will allow the user to set up a virtual seismic survey on either the salt or overthrust model data. The user will be able to control all aspects of the shot and receiver layout. The result of this operation will be a reasonably sized collection of traces, which will be automatically extracted from the appropriate shot files in the storage facility.

The final method for extracting data from the modeling project data will be a program, which uses the shot and receiver information from a user-provided SEG-P1 file to drive the data extraction process. The SEG-P1 file is an industry standard file that contains seismic survey details. This method allows investigators to use their favorite survey tools to define the shot and receiver locations. The same low-level data extraction tools used by the X-based graphical interface described earlier will be employed by this method for creating the subsets. Figure 13 shows a menu for selecting the desired subsets of SEMD.

The current data storage and data access mechanism is a temporary one. Plans are under way to identify a permanent site to store the data and a way to make copies of the large volumes of the data. The SEG and EAGE will be involved in this effort. For the latest arrangements and updates see the SEMD website at *http://www.seg.org/research/3-Dmodel/index.html*.

CLASSIC DATA SETS OF SALT MODEL

To provide industry and academia with manageable, consistent, and useful subsets of the SEM data set, several "Classic Data Sets" (CDS) have been defined. These data sets will be made available upon request. In the near future, access to these data sets will be

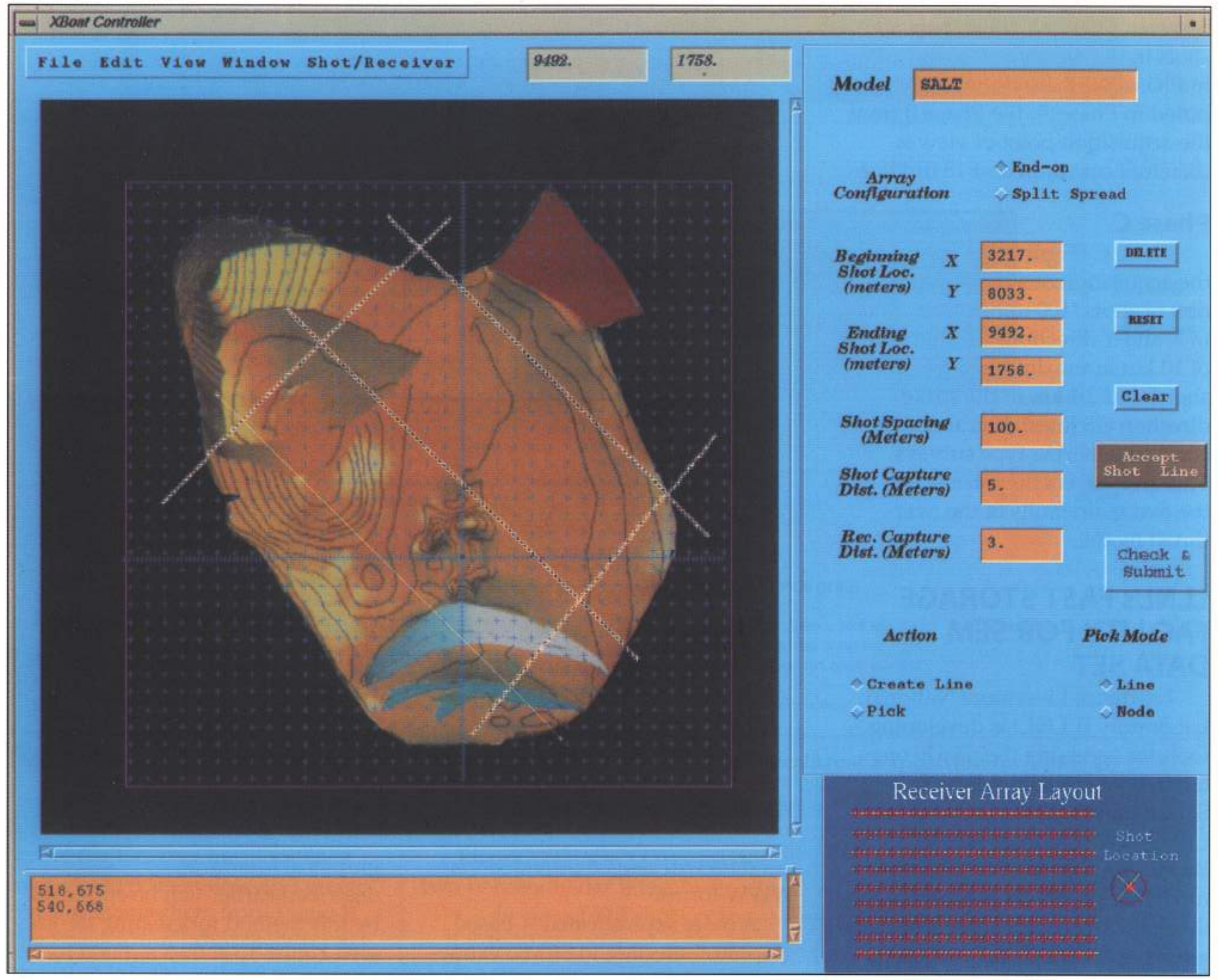


Figure 13. A display of the menu-driven program to retrieve desired subsets of the SEMD (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists; permission for use on CD-ROM courtesy of Datapages, Inc.).

provided through the Internet and by tape.

Phase A Classic Data Set 1 - CDS A0

This is comprised of a raw shot gather at grid node 384,441 with a square of 279 x 279 receivers. In addition, it includes a simulation of 3-D plane wave source (zero-offset data). Sample interval is 8 ms, recording time is 5 s. Total data set size is approximately 193 Mbytes. This location is at the intersection of Phase 1, Line 1 and Phase 2, Line 2 at the crest of the salt.

Phase A Classic Data Set 2- CDS A1

This is Line 1 (the yellow line on Figure 10) with 138 shots simulating a 6-streamer marine acquisition with 65 groups per streamer. Group interval is 40 m, near offset is 160 m, and far offset is 2760 m. Sample interval is 8 ms, and recording time is 5 s. Data set size is approximately 133 Mbytes. **CDS A2** is the same as CDS A1 except it contains the blue line on Figure 10, perpendicular to line 1 as described earlier.

Phase B Classic Data Set 1. CDS B-1

This data set includes selected shots from Phase 2. It contains 156 shots of streamer marine acquisition with 65 groups per streamer. Group interval is 40 m, near offset is 160 m, and far offset is 2760 m. Sample interval is 8 ms, and recording time is 5 s. Data set is approximately 150 Mbytes.

Other classic data sets for specific applications (e.g. velocity analysis) are under development.

Phase C Classic Data Sets

There are three Phase C Classic Data Sets. Data set 1 is a narrow azimuth towed cables data set. A Single Sail Direction is used. There are 50 lines with 160 m crossline spacing, 95 shots/line at 80 m shot spacing. Eight streamers are used with the following locations from the boat (-140, -100, -60, -20, 20, 60, 100, 140). There are 68 groups/streamer with 40 m group interval.

Minimum inline offset is 0 m and maximum line offset is 2680 m. This provides 20 meter inline and crossline CMP coverage of 17 fold. The data set size is ~6.4 Gbytes.

Data set 2 is a wide azimuth towed cables data set. A Single Sail Direction is used. There are 25 lines with 320 m crossline spacing, 95 shots/line at 80 m shot spacing. Eight streamers are used with the following location from the boat (-280, -200, -120, -40, 40, 120, 200, 280). There are 68 groups/streamer with 40 meter group interval. Minimum inline offset is 0 m and maximum line offset is 2680 m. This provides 20 m inline and crossline CMP coverage of 17 fold. The data set size is ~3.2 Gbytes.

Data set 3 is an Ocean Bottom Cable type of Acquisition. Shotlines are perpendicular to a pair of cables with following specifications: shot interval: 80; group interval: 40; cable length: 5720 m (144 groups per cable); number of cables: 2; cable spacing: 40; shotline length: 2480 m (32 shots); maximum inline offset: 2860 m (half the cable length); maximum crossline offset: 1260 m (half the shotline length); maximum offset: 3125 m; crossline swath moveup: 320 m (4 shots); inline swath moveup: 720 m (18 groups); inline fold: 4 (144 group/18 group moveup/2); crossline fold: 4 (32 shots/4 shot moveup/2); total fold: 16. This geometry has similar fold, midpoint spacing, and offset range to the narrow azimuth data. The inline offset is about twice the crossline offset, making it similar to the Western Mega survey.

CLASSIC DATA SETS OF OVERTHRUST MODEL

Classic data sets correspond to selections of common interest for research application or benchmarks small enough to be easily distributed. These selections were established in July 1996 after discussion between the "3-D Marmousi" EEC project participants (Thermie Program).

The overthrust classic data are available:

– using the following URL for classic data sets C1, C2 and C3: http://wildcat.llnl.gov/SSD/

– using tape copies. Requests should be addressed at IFP to Laurence Nicoletis (E-mail: Laurence.Nicoletis@ifp.fr). The cost of tape copying will be charged.

All sizes are given for E-SEP format. For SEGY, sizes should be multiplied by 1.09.

- *2-D inlines and cross-lines profiles*: A1-dip (~300 Mbytes) and A1-strike (~193 Mbytes)

From the 2 shot lines (dip and strike), select only the inline and cross-line receivers (Y receiver = Y source or X receiver=X source) with 25 m between receivers, 321 receivers per line (split-spread in the directions parallel and perpendicular to the acquisition).

- *Wide profiling acquisition*: A2-dip (~1202 Mbytes) and A2-strike (~774 Mbytes)

From the 2 shot lines (dip and strike), a split-spread wide profile with 8 receiver lines (plate 10) was proposed for a maximum 4000 m inline offset, 50 m between lines, 25 m between receivers (321 receivers per line), and 50 m between sources. The wide line is split-spread in the direction of acquisition, thus allowing for reciprocal time studies. Due to the choice of an even number of lines and the symmetry with respect to the navigation line, the inline receiver line (which is available in A-1) is not included.

- *Normal incidence VSPs*: A3-NIVSP (~12 Mbytes)

It includes the 52 vertical (zero-offset) VSPs recorded (plate 5) with receivers from Z=25 m down to Z= 4025 m.

- *2-D walk-away in pressure* A3-OVSP (~30 Mbytes)

It includes 126 offset VSPs recorded in well A1 during phase A (plate 6) with receivers from Z=25 m down to Z= 4025 m.

- *2-D walk-away in three components (gradient of pressure)* A3-OVSP-3C (~89 Mbytes)

It includes the three components of the pressure gradient in well A1 (computed by first order finite differences from five adjacent wells) in order to simulate 3-C data. There are 157 traces from Z=50 m down to Z= 3950 m

- *Reverse 3-D walk-away* A3-R3-DWA (~263 Mbytes)

It includes the 12 down-holes shots in well A1 with surface-receivers decimated to 50 m and up to 3000 m of offsets (plate 7).

- *Patch data for the dip and strike shot lines* A4-dip (~1520 Mbytes) and A4-strike (~869 Mbytes)

The layout is a swath acquisition of 8 double lines without line overlap. It is interesting because it includes Ocean Bottom Cable acquisition which shows a growing interest.

- *Swath data from Phase B acquisition* B2 (~12 Gbytes)

Using Phase B data, it is not possible to follow the industry standard which would require more sampling in the strike direction. As the dip direction is the best sampling direction for sources, it was

decided by Fernand Baixas (CGG) to build cross-spreads with receiver lines sampled at 50 m in the strike direction. The layout is a swath-type acquisition over 12 double receiver lines (double lines are preferable to single lines in order to have squared bin of 25 m) for a maximum 30 fold coverage. Subset swaths could be conveniently subsampled. A good offset repartition in X and Y (with regard to the problem of shallow velocity estimation) is preserved. The drawback is that this swath has large offsets only in the strike direction.

- *Patch data from Phase B acquisition* B3 (~13 Gbytes)

The layout is a swath acquisition of 8 double lines without line overlap . This leads to a good fold and good azimuth-offset distribution (it has most azimuths represented with offset larger than 2000 m).

- *Zero-offset data from Phases B and* C C1 (~8 Mbytes)

- *Marine acquisition from Phase C* C2 (~7 Gbytes)

A marine acquisition has been defined with 9 streamers 50 m apart, 50 m trace interval and 3000 m maximum offset (split-spread profiles). The choice of an odd number of lines and the symmetry with respect to the navigation line means that we do have the inline receiver line.

- *Twenty-five selected shots* C3 (~972 Mbytes)

The 25 selected shots are located in a square corresponding to a complex part of the model (convergence of the two main thrusts): The shots are located at X= 7550m ± N 100 m and at Y = 11375 m ± N 100 m with N= 0, 1, 2. Receivers are decimated to a 50 m interval in X and Y, choosing a minimum offset equal to 0 m.

SOME RECENT APPLICATIONS

GOVERNMENT-SUPPORTED PROJECTS

TESTING ADVANCED COMPUTATION TOOLS FOR 3-D SEISMIC ANALYSIS USING THE SEG/EAGE 3-D MODEL DATA SET (HOUSE)

As a collaboration among twenty-eight oil and gas industry companies, three U.S. national laboratories, and six universities, this project is an ambitious effort to test existing imaging methods and develop faster methods of imaging and modeling 3-D seismic data. Another goal of the project is to demonstrate the usefulness of the SEG/EAGE model data set. The project started in 1995 and will continue another year or more. This collaboration has primarily focused on the salt structure, as a result of the keen interest of many participants in subsalt plays in the Gulf of Mexico. This work is organized as a series of sub-projects that emphasize two main areas: modeling, and imaging and inverse methods.

The modeling studies include collecting and processing of data from a scaled physical model of the salt structure, studying the usefulness of incorporating wave conversions (*P/S*) in imaging, and increasing the speed of numerical modeling by developing a faster approach to finite-difference solution to the wave equation. Notable accomplishments so far have included:

1) collection of two multi-Gigabyte data sets from the physical model, one a traditional marine acquisition geometry, the other using vertical cables of receivers;
2) modeling of wave conversions related to a salt structure show that converted waves may be crucial in some situations for imaging the bottom of salt bodies; and
3) development of a new algorithm for forward modeling that exploits the computational efficiency of explicit finite-difference methods while retaining the unconditional stability of implicit methods.

Imaging and inverse methods studies include developing faster approaches for 3-D imaging and 3-D velocity analysis and model building. The faster imaging methods use sophisticated partial prestacking and approximate imaging methods. Increasing the speed and reliability of 3-D velocity analysis and model building exploits automation of event picking in prestack gathers and the use of a new approach to statics estimation that should improve the reliability of the statics. Notable accomplishments of this portion of the project have been:

1) development of a method that exploits the range of source receiver azimuths in conventional marine data acquisition to allow a partial stack of data before migration and thereby reduce the time required for migration;
2) demonstration of a 100-fold reduction in the time needed for migration by adapting a conventional (serial) migration program to a massively parallel computing system;
3) development and testing of an automated approach to accurately tracking seismic events in prestack data that should be able to reduce the amount of time needed for 3-D velocity analysis by 90% or more; and
4) application of a recently developed solution for global optimization problems to the estimation of residual statics in seismic data, so the global minimum solution can be found within a feasible amount of computing time.

Results of work from the project have been presented in numerous presentations at professional meetings, notably of the SEG, as well as papers in peer-reviewed journals.

GULF OF MEXICO SUBSALT SEISMIC IMAGING PROJECT (FEHLER)

The Gulf of Mexico Subsalt Seismic Imaging Project was initiated under the Cooperative Research and Development Agreement, CRADA- LA94C1051, between the DOE and several oil companies. Under this project, an exploding reflector modeling experiment has been performed, and the data have been migrated using the salt model velocity grid of SEM. Figures 14 and 15 show some of the migration results. Figure 14 shows the match between the original model surfaces and the migrated events. In this figure, we see a thin sand lens below salt and only the top portion of a second sand layer also below salt. In Figure 15, we see the event imprint of two thin lenses on a depth section. These results are encouraging in that we see that it is possible to image events below salt in the SEM.

3-D PRESTACK DEPTH MIGRATION OF A SUBSET OF THE SEG/EAGE SALT MODEL DATA SET (BURCH, OBER)

As a test of a 3-D, implicit finite-difference, prestack depth migration code, Sandia National Laboratories has depth migrated a subset of the SEG/EAGE salt model data set. This work is part of an ACTI project called 3-D Seismic Imaging of Complex Geologies. Extracting three shots at a time, 45 shots were downloaded from the SEG/EAGE salt model data archived at Lawrence Livermore National Lab via the Internet. Each shot covered a fully populated 4 km by 4 km region and was about 100

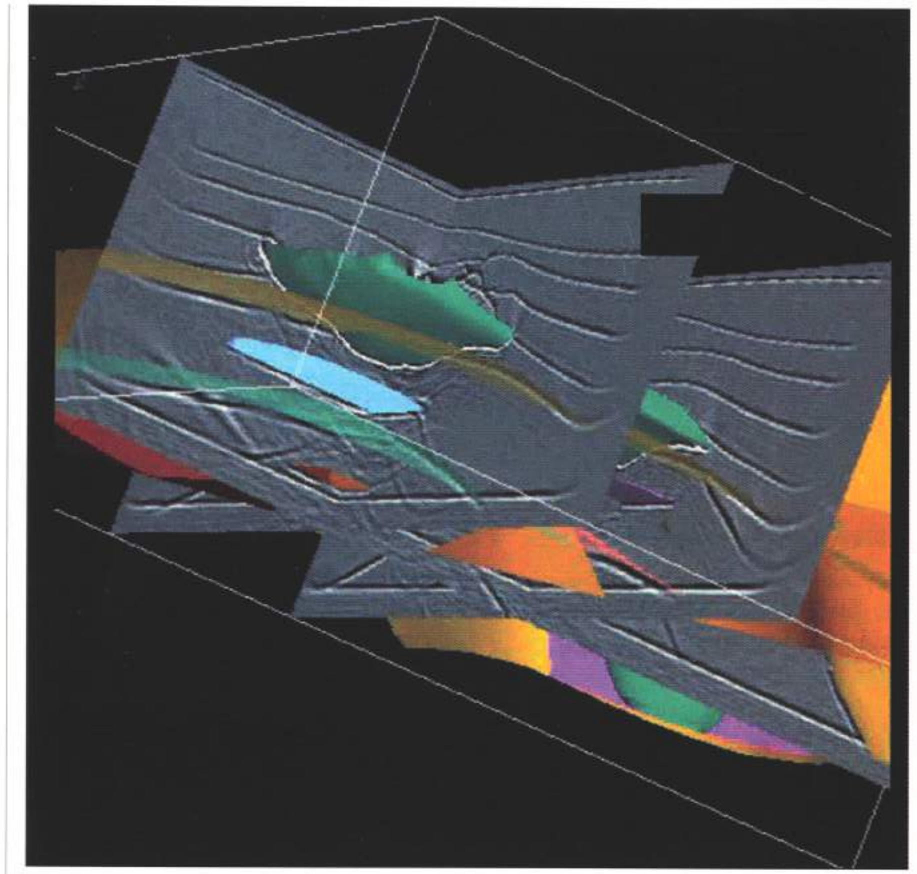


Figure 14. 3-D migrated volume overlaid on the 3-D geologic model (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists, courtesy of Gulf of Mexico Subsalt Seismic Imaging Project, CRADA LA94C1051; permission for use on CD-ROM courtesy of Datapages, Inc.).

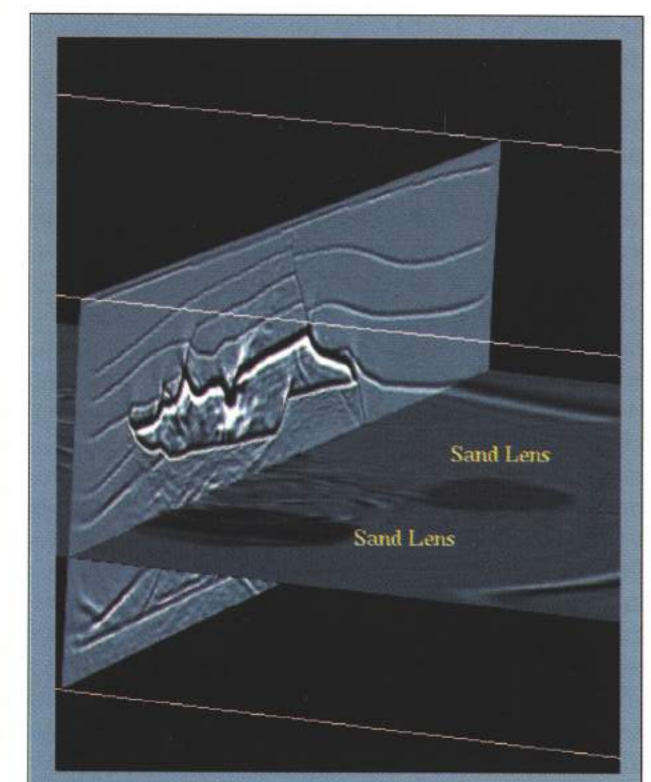


Figure 15. Imaged thin sand lens below salt (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists, courtesy of Gulf of Mexico Subsalt Seismic Imaging Project, CRADA LA 94C1051; permission for use on CD-ROM courtesy of Datapages, Inc.).

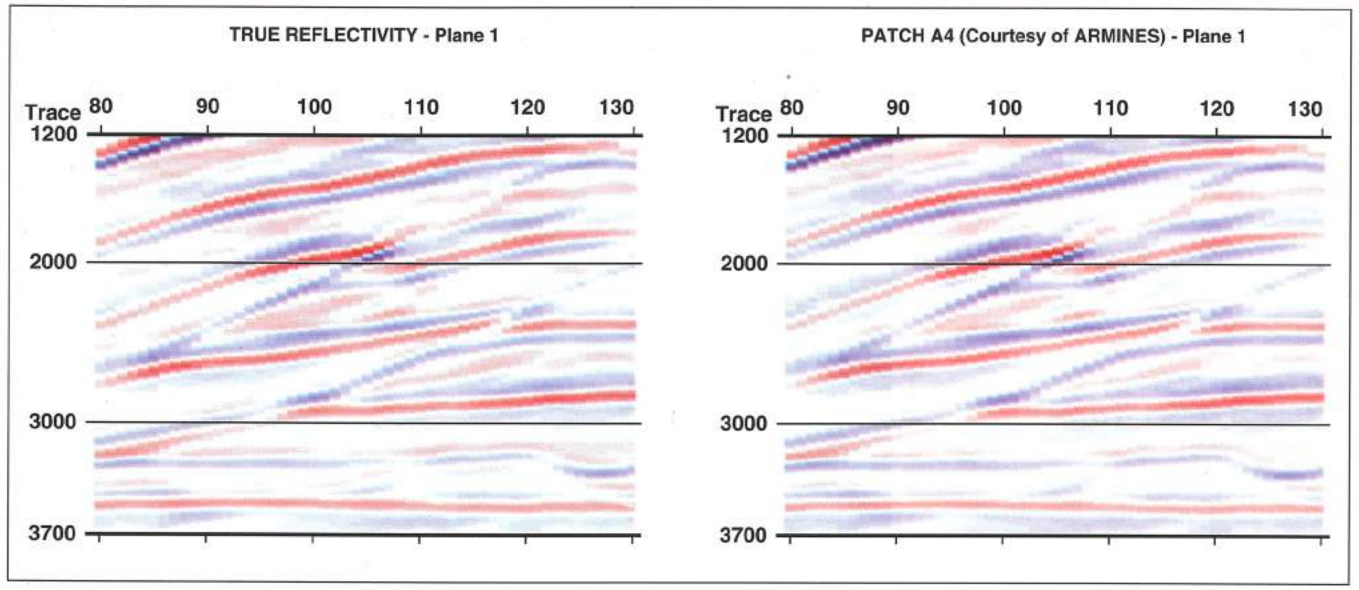


Figure 16. Quantitative Imaging of the overthrust model using Patch survey (Courtesy of ARMINES, Thermie Project "Marmousi 3-D").

megabytes. For a set of three shots, it took approximately two days to extract from the archive and another day to download. The volume imaged was a 600 by 600 by 210 grid which represented a 12 km by 12 km region, whereas the region available with the SEG/EAGE salt model data set is 13.5 km by 13.5 km. Each shot was migrated over a 200 x 200 x 210 grid. The fold of the data varied from eight to a maximum of fifteen. The migration was done on the INTEL Paragon at Sandia, which has more than 1800 processors and is where a portion of the SEG/EAGE salt model data set originally was generated. The migration was done as blocks of time were available on the Paragon.

Each shot was migrated using from 32 to 128 processors, with the average time to migrate a single shot being approximately 40 minutes using 64 processors. Even though only a small percentage of the total shots available from the SEG/EAGE salt model data set was migrated, the results are quite good, which indicates the data extraction and the depth migration are working. Other tests on the migration code include the French model, the Marmousi data set, and field data sets from the Gulf of Mexico, the North Sea and West Texas.

Fast 3-D Seismic Modeling and Prestack Depth Migration Using Generalized Screen Propagators (Toksoz, Fehler, Wu)

Two-dimensional slices through the SEG/EAGE salt model have been used as test cases for modeling and migration using Generalized Split-Step Fourier methods by Huang and Fehler (1997) as part of an ACTI project that is funded by the DOE. In the migration studies, 2-D exploding reflector data were generated for slices through the salt model using finite difference schemes. The data were migrated using various implementations of split-step Fourier methods that are being developed and tested by participants in the project. In the migration studies, differing schemes were used to partition the model into sections in an attempt to reduce the large velocity contrasts in the model and improve the image quality. More recently, participants in this project have found a method that does not require the partitioning to result in high-quality images. Huang and Fehler (1997) investigated the reliability of forward modeling the salt data using various implementations of the split-step Fourier method. A comparison of forward modeling of a 2-D section of the salt model using the Split-Step Fourier method and finite difference of the acoustic wave equation appears in Sato and Fehler (1997).

THERMIE PROJECT (Nicoletis)

The Thermie project "Marmousi 3-D" is a two-year project (ending in June 1998) partially supported by EEC within the frame of the THERMIE program.

The participants to this project are:

- Institut Français du Pétrole (France)
- CGG (France)
- Dipartimento di Elettronica ed Informazione, Politecnico di Milano (Italy)
- Laboratory of Seismics and Acoustics, Delft University of Technology (The Netherlands)
- ARMINES, Ecole des Mines de Paris (France)
- Geophysikalisches Institut, Universität of Karlsruhe (Germany).

The main objective of the project is the assessment, using the SEG/EAGE 3-D overthrust synthetic data, of new innovative 3-D prestack processing techniques aimed to improve the accuracy of the results in terms of depth localization, spatial resolution and true amplitude reflectivity. The following questions are addressed:

- ability of the prestack interpolation techniques to recover data which are aliased in the shot or receiver domain;
- degree of accuracy of superficial velocity variations corrections found from refraction analysis and tomography,
- effectiveness (in terms of spatial resolution as well as in quantitative estimation of reflectivity) brought by true amplitude Kirchhoff type prestack migration;
- evaluation of full waveform wave equation prestack migration;
- evaluation of new techniques for macro-model verification (focus point gather analysis and waves image techniques),
- Value of VSPs and pseudo VSPs.

Three papers related to this project were presented at the 1997 EAGE annual meeting (Operto et al., 1997, Clochard et al., 1997, Mann et al., 1997). Figures 16 and 17, taken after the first two papers, show prestack imaging results obtained with patch A4 and 3-D reverse walk-aways respectively. The prestack imaging techniques were ray-Born true amplitude algorithm.

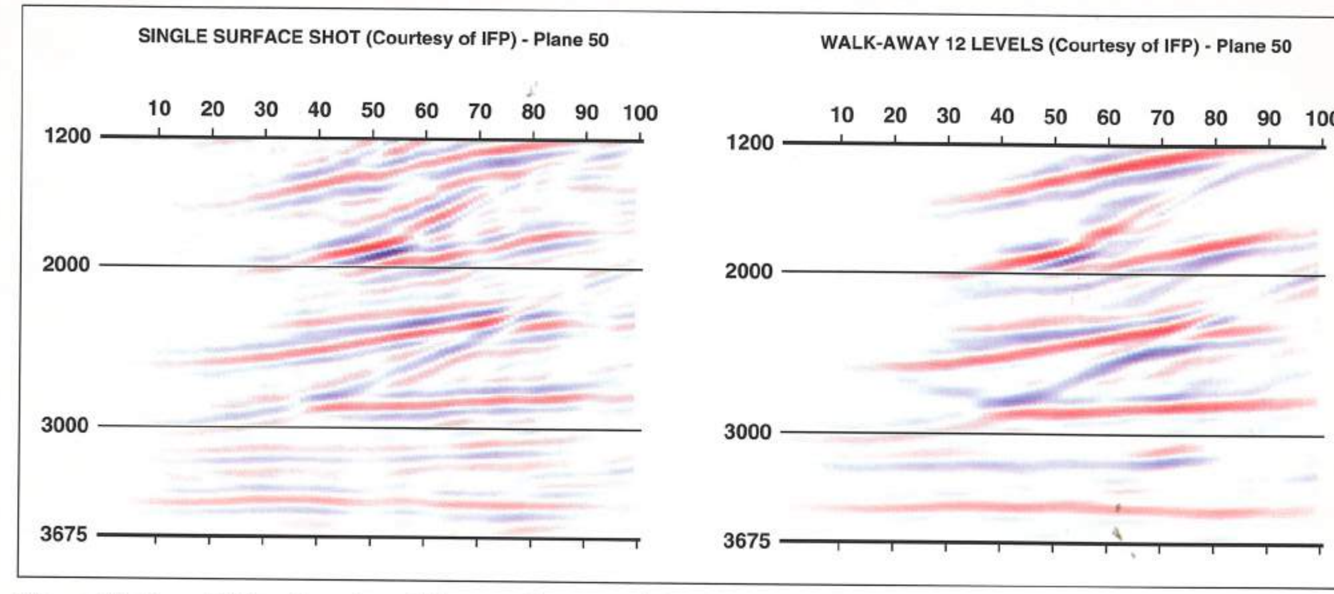


Figure 17. Quantitative Imaging of the overthrust model using 3-D walk-away (Courtesy of IFP, Thermie Project "Marmousi 3-D").

OTHER APPLICATIONS AND ACTIVITIES:

Can We Image Below Salt?

O'Brien and Gray (1996) use the AA' 2-D velocity salt model profile shown in Figure 3 and the respective "exploding reflector" zero-offset section of Figure 5 to answer this question. They conclude that the SEM data provide the necessary challenge for improving the imaging software. In addition, other processing issues such as multiple elimination techniques, can be tested using these SEM models. For example, see Figure 18 which shows their final imaging result after surface multiple elimination and limiting range of the data to 0 - 8000 feet.

1996 SEG Workshop on SEG/EAGE 3-D Models

A workshop on the public domain models was held at the 1996 SEG Annual Meeting in Denver and the 1996 EAGE meeting in Amsterdam. Many presentations were made on current modeling projects using the SEG/EAGE salt model and overthrust model. The public availability of these models and their huge sizes make them test beds for algorithm testing. In addition to velocity analysis and migration, these also include data compression and both academic and industrial modeling codes. Some of the material in these workshops were in connection with the results of the European Community (THERMIE) and the DOE (ACTI) sponsored projects highlighted earlier.

One reservation expressed on the salt model was since the velocities are excessively slow, wave equation modeling is expensive, and the velocities are not blocky enough for current 3-D raytracers. This makes it difficult to compare different modeling results such as raytracing and finite difference. Several different representations of the salt model have been created to test different modeling algorithms. Among them were: Wendell Wiggins, of Western, where he downloaded the SEG salt model description and created a tetrahedral mesh representation of the model. This representation is 79

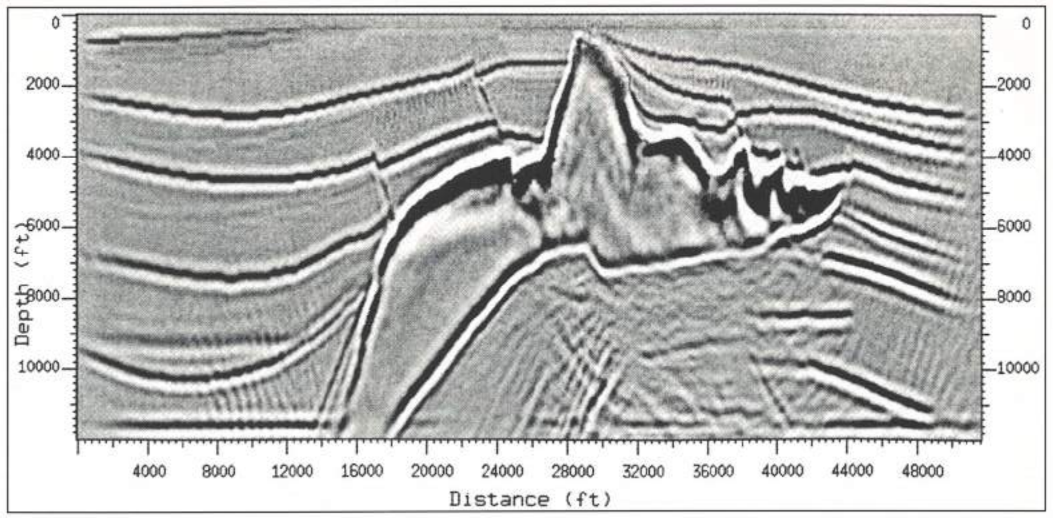


Figure 18. Imaging below the salt body after multiples elimination (F. Aminzadeh, © 1996, reprinted by permission of the American Association of Petroleum Geologists, courtesy of O'Brien and Gray, 1996; permission for use on CD-ROM courtesy of Datapages, Inc.).

Mbytes compared to the 384 Mbytes required by the gridded version of the model. It is able to accurately represent the grid velocities to within 1%. Using this model, traveltimes were calculated through this piecewise-linear velocity model. Also, Victor Pereyra, of Weidlinger Associates, described the results of creating a blocky model version of the salt model using B-spline patches. This model is a close approximation of a Physical model constructed at the Allied Geophysical Lab. Using this model representation both zero-offset and shot point raytracing has been performed. Finally Phil Bording, of UT, showed the results of Ocean Bottom Modeling in Two Dimensions. The salt model grid was downloaded and used to perform 2-D finite difference modeling using an Ocean Bottom survey scheme.

CONCLUSIONS

The SEM project goal has been to design two 3-D models, salt and overthrust, and simulate realistic 3-D surveys over these complicated structures through numerical calculations. The data sets generated through this project in four national DOE laboratories will be made available to industry and academia. Many industry and academic groups have already begun using and testing the data sets for various applications. In addition several government-supported projects under Advanced Computational Technology Initiative (ACTI) from the United States and THERMIE from European Union have used these data sets as key components of their test beds. The strong support and involvement of industry at different stages of the SEM project has been a key to its success to this point. We expect increased utilization of these data sets over the next several years. For additional details and recent updates in connection with these models see: *http://www.seg.org/research/3-D-model/index.html*.

ACKNOWLEDGMENTS

This has been a truly collaborative effort with contributions from the oil industry, academia, and national laboratories. We would like to specially thank Kay Wyatt of Phillips Petroleum, Fernand Baixas of CGG, Fabien Bosquet of Gocad, Pierre Duclos and Laurence Nicoletis of IFP, Norm Burkhard of Lawrence Livermore National Laboratory, Leigh House of Los Alamos National Laboratory, and Fabio Rocca of Politecnico di Milano who have made significant contributions during the course of this project. Also we would like to thank the SEG and EAGE executive committees for their continued support and encouragement, in particular those of Fred Hilterman and Rutt Bridges of SEG and James Smethurst of EAGE.

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Appendix A

TABLE OF CONTENTS OF THE SALT CD-ROM

1 - Readme,
2 - Htmls,
3 - Model Surfaces
4 - Salt@@ as a zipped file (2-D & 3-D)
5 - Phase A Data set 1 Segy
6 - Phase A Data set 2 Segy

The file size is ~37 MBytes for items 1 through 4, ~135 Mbytes for item 5, and ~140 Mbytes for item 6.

Appendix B

TABLE OF CONTENTS OF THE OVERTHRUST CD-ROMS

1 - html pages, To look at them, you have to type in the open URL dialog of your browser:
>netscape home-page.html
(You need "xanim" for displaying the movies.)
2 - The GOCAD surfaces of the overthrust model have to be read with GOCAD software.
3 - Classic data set A1 - marine acquisition
- dip line (y=11 375 m), 312 shots
  name of the file: a1-dip-marine.segy
  size of the file: uncompressed: ~320 420 240 bytes
  gzipped: ~230 890 884 bytes
- strike line (x=7600 m), 201 shots
  name of the file: a1-strike-marine.segy
  size of the file: uncompressed: ~211 302 840 bytes
  gzipped: ~164 326 891 bytes

Classic data sets are written in files:
- zero offset traces, 4900 shots
  name of the file: overthrust-zero_offset.segy
  size of the file: uncompressed: ~8039600 bytes
  gzipped: ~6 428 445 bytes

The overthrust model is in SEP format. It is a binary format with floating point number of 4 bytes (IEEE arithmetic representation). The data file in "direct access" is organized
- in traces of n1=801 samples in the x-direction,
- with n2=801 traces in the y-direction,
- including n3=187 planes at constant z.

The ASCII header file includes the information n1, n2, n3; but also the values d1=25.0, d2=25.0, d3=25.0 respectively, providing the unity in the x, y and z direction.
- name of the data file: overthrust.vites
- name of the header file: overthrust.vites
- size of the file: uncompressed: ~479 917 548 bytes;
  gzipped: ~145 938 034 bytes.

Appendix C

The CD-ROMs have been written to be compatible with MacOS, Windows 95/NT, and UNIX. The HTML files in the Overthrust CD Disc 1 are also compatible with Windows 3.1. UNIX files are compatible with the Rockridge format (RRIP).

Windows users should run SETUP.EXE on Overthrust Disc 1 to obtain the benefits of WebCD's (TM) full-text searching and other enhancements in the HTML. A short tutorial will play on the first use and is available in online help at any time. Running setup will also create program and menu icons/items that make for easy entry into the HTML.

WebCD creates a special HTML file called HOME.HTML which points to the index HTML file in the archive. Non-Windows users may experience difficulty with certain browser/OS combinations if they choose to enter the HTML archive via this pointer file. The actual home page, through which Macintosh and UNIX users may access the archive, is accessed through a file named DOCS/00000/00008.HTM.